

Diffusivity-Free Turbulence in Liquid Metal Rotating Rayleigh-Bénard Convection Experiments

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Convection in planets and stars is predicted to occur in the “ultimate regime” of diffusivity-free, rapidly rotating turbulence in which flows are unaffected by viscous and thermal diffusion. Boundary layer diffusion, however, has historically hindered experimental access to this regime. Here, we utilize the boundary-independent oscillatory thermal-inertial mode of rotating convection to realize the diffusivity-free scaling in liquid metal laboratory experiments with additional validation from direct numerical simulations. This oscillatory style of convection arises in rotating liquid metals (low Prandtl number fluids) and is driven by the temperature gradient in the fluid bulk, thus remaining independent of diffusive boundary dynamics. We triply verify the existence of the diffusivity-free regime via measurements of heat transfer efficiency Nu , dimensionless flow velocities Re , and internal temperature anomalies θ , all of which are in quantitative agreement with planar asymptotically reduced models. Realizing theoretical diffusivity-free scalings in desktop-sized laboratory experiments provides the validation necessary to extrapolate and predict the convective flows in remote geophysical and astrophysical systems.

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Rotating diffusivity-free (RDF) turbulent convection is theorized to occur in the convection zones of stars and the fluid cores of planets, where it drives vortical flows, jets, and the dynamo action that sustains global-scale magnetic fields [1–3]. The RDF regime is characterized by strong rotating turbulence that is unaffected by either the fluid’s microscale viscosity (ν) or thermal diffusivity (κ), representing a subset of the inviscid (Coriolis-Inertial-Archimedean) “CIA” scaling regime that is independent of κ in addition to ν [see Refs. [4,5] and Supplemental Material [6]]. Fluid physics researchers have long sought to validate this end-member rotating turbulent regime through measurements of heat transfer efficiency in both numerical simulations and laboratory experiments [e.g., Refs. [31,32]]. It remains an essential question as to whether the theorized RDF regime can be attained in a laboratory setting and extrapolated to natural settings.

The canonical system for studying rotationally constrained turbulent flows is rotating Rayleigh-Bénard convection (RRBC) [32]. In RRBC, a fluid layer bounded by

two parallel no-slip plates is heated from below, cooled from above, and rotated about its central vertical axis. Scaling laws that relate global heat transport (Nusselt number, Nu , the ratio of total to conductive heat flux) and bulk flow velocity (Reynolds number, Re , the ratio of inertial advection to viscous diffusion) to the buoyancy forcing (Rayleigh number, Ra , the ratio of thermal buoyancy to diffusion), global rotation period (Ekman number, E , the ratio of viscous diffusion to coriolis acceleration), and material properties (Prandtl number, Pr , the ratio of viscous to thermal diffusion) enable the extrapolation of laboratory-numerical findings to more extreme geophysical and astrophysical scales [33–38]. (See Table I in Appendix A for parameter definitions).

The scaling predictions for the RDF regime are derived by enforcing the constraint that thermal and viscous diffusion have no effect on the total heat transported through the system nor the internal flow velocities, and assuming that the system is rapidly rotating ($E \ll 1$; $Ro \ll 1$) [Ref. [39] and see Supplemental Material [6]]. The global heat transport prediction for rapidly rotating diffusion-free (DF) convection follows

$$Nu - 1 = C_J Ra^{3/2} E^2 Pr^{-1/2}, \quad (1)$$

where C_J is a constant prefactor dependent upon the convective driving mechanism and the geometry of the

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fluid layer. This value was determined by Julien *et al.* [39] to be $C_J \approx 1/25$ in doubly periodic planar models of the asymptotically reduced RRBC equations across a range of low to moderate Pr values. Scaling predictions for the internal quantities are determined from a torque balance between the inertial and buoyancy terms of the vorticity equation describing rotating flows, neglecting viscous diffusion [e.g., Ref. [40] and see Supplemental Material [6]]. Assuming any scaling coefficients other than C_J are order unity, the prediction for the internal flow velocity is

$$Re = C_J^{2/5} Ro_c^2 E^{-1} = C_J^{2/5} Ra E Pr^{-1}, \quad (2)$$

and for the internal temperature fluctuation is

$$\theta/\Delta T = C_J^{3/5} Ro_c = C_J^{3/5} Ra^{1/2} E Pr^{-1/2}, \quad (3)$$

where θ is the root-mean-squared temperature perturbation, and $Ro_c = (Ra E^2 Pr^{-1})^{1/2}$ is the convective Rossby number (representing the ratio of buoyancy to coriolis forces) [38]. These scalings have yet to be unambiguously found in a closed cell RRBC laboratory setup, thus raising the question of their applicability to enclosed natural systems (cf. Ref. [41]).

The fundamental barrier to achieving diffusion-free convection in RRBC lies in the physical boundaries through which heat is supplied and extracted. Boundary layers throttle energy transfer through the system. In most RRBC cases, the primary mode of convective instability is that of steady convection, which is thermally controlled by the conditions at the boundaries [42,43]. The critical value of the Rayleigh number for which steady convective motions first develop (denoted as Ra_S) is determined from a balance between friction and the coriolis and pressure gradient forces, such that the steady mode is considered a viscously dominated convective instability [44,45]. Consequently, heat transfer in typical steady RRBC is dominated by boundary layer diffusion [e.g., Refs. [38,46]], which impedes the system from reaching the asymptotic RDF scaling limit.

Lateral boundaries in RRBC give rise to additional sidewall-attached convective instabilities. These “wall modes” manifest in the form of flow structures that travel azimuthally around the periphery of the tank, and are also a viscous instability [47]. Between contributions from steady bulk convection and wall mode convection, RRBC heat transfer is often strongly influenced by diffusive effects.

In order to mitigate boundary contributions in convection studies, researchers have employed innovative techniques to bypass the boundaries altogether. Numerically, this has been achieved through the use of ghost layers (i.e., internal heating and cooling layers) or forced decoupling of boundary layers [48,49]. Experimentally, radiative heat deposition directly into the fluid bulk [50,51] has recently found the asymptotic heat transfer scaling exponent, but a

very different value of the prefactor than that of Julien *et al.* [39] due to the differing means of thermal energy injection. Their results may apply to the rotating convective turbulence present in gas planets and stars; however, it is uncertain that they apply to terrestrial fluid environments where convection is still driven by fluxing heat through finite, solid boundaries. Thus, bounded RRBC systems have yet to yield unambiguous asymptotic scalings, raising the dual concerns (i) that standard laboratory-scale devices may be unable to realistically simulate geophysical turbulence or (ii) that DF scalings do not exist in natural convection enclosed by solid boundaries [52–56].

To address these questions, we utilize the thermal-inertial oscillatory mode of convection that exists in low Pr liquid metal RRBC [45,57–60]. Contrary to steady convection, which is subject to thermal boundary conditions, oscillatory convection is driven entirely by the temperature field in the bulk and does not sample the boundary layer thermally. Zhang and Roberts [58] showed that oscillatory convection is described by a thermal-inertial wave, arising from a balance between inertia and coriolis acceleration, with no dependence on the nature of the boundaries or diffusive effects at dominant order. This thermally driven inertial instability arises exclusively in rotating low $Pr < 1$ fluids, like liquid metals and plasmas. The critical Ra for which oscillatory modes onset (denoted as Ra_O) occurs at lower Ra than that for steady convection (Ra_S), such that thermal-inertial oscillations are considered the preferred mode of convection when the Prandtl number is sufficiently small [44]. Here, by focusing on the oscillatory mode in rotating liquid gallium ($Pr \approx 0.027$) convection experiments, we show that the inertial asymptotic DF scalings (1)–(3) can be realized in a desktop-sized RRBC cell, and are in good quantitative agreement with Julien *et al.* [39]’s asymptotically reduced low to moderate Pr RRBC models, further validating both laboratory and multiscale asymptotic methods.

UCLA’s RoMag device is used to conduct these experiments. The setup [Fig. 1(a)] features a right cylindrical convection cell with a height of $H = 40.0$ cm and a diameter of $D = 19.9$ cm, yielding an aspect ratio of $\Gamma = D/H \approx 1/2$. The cell is constructed with a thin stainless steel sidewall positioned between two copper end blocks. Heat is supplied through a basal heating pad, while a heat exchanger plate, connected to a recirculating chiller, removes heat at the top. After equilibration, both the top and bottom copper end blocks are maintained at fixed temperatures for the duration of the experiment. The Biot number, which characterizes the isothermality of the boundaries relative to the bulk, is small at $Bi \lesssim 0.2$. The convection cell is affixed to a rotating platform that spins the cell about its vertical axis. We carry out a systematic survey, varying the Rayleigh and Ekman numbers by approximately 2 orders of magnitude each ($10^7 \leq Ra \leq 10^9$ and $3 \times 10^{-7} \leq E \leq 10^{-5}$).

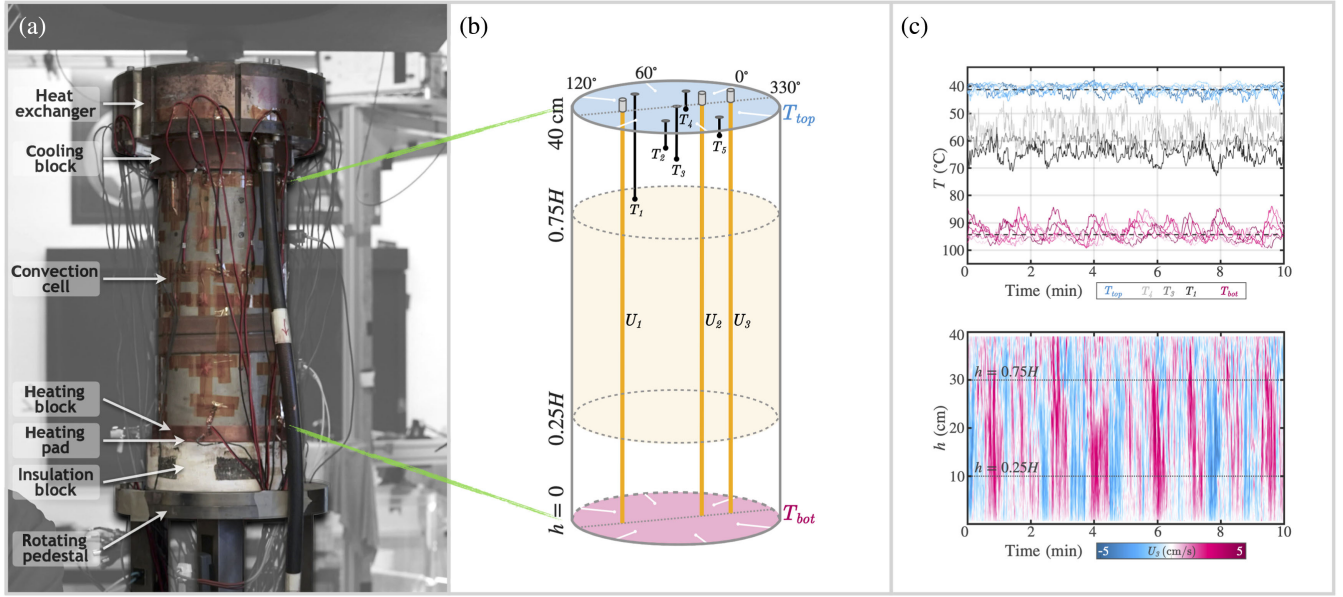


FIG. 1. Rotating laboratory setup. (a) The RoMag device at UCLA with the $\Gamma \simeq 1/2$ tank in place. Heat is supplied to the base (“heating block”) by a heating pad and extracted from the lid (“cooling block”) by a heat exchanger routed to a recirculating chiller. The cell is filled with liquid gallium and wrapped in layers of insulation (not pictured). Red and black wires connect to thermistors and Doppler transducers. (b) Schematic of measurement locations. White lines at the cell boundaries mark 12 thermistors embedded within the blocks. Black dots denote five internal thermistors. Orange lines show the 1D Doppler sensing paths. (c) Example time series for a turbulent oscillatory case. Top: thermistor data, with pink (blue) for bottom (top) boundaries and gray for internal temperatures. Bottom: velocimetry data, with pink (blue) for upward (downward) flow. The middle 50% of the chord is used to compute the rms velocity (denoted with dotted lines). The case shown corresponds to parameters: $Ra \simeq 10^9$, $E \simeq 8 \times 10^{-7}$, $Ro_c \simeq 0.16$, $Ro_z \simeq 0.01$, and $Re_z \simeq 2 \times 10^4$.

For each experiment, we acquire measurements of temperature, heat flux, and velocity. Thermistors embedded within the top and bottom thermal blocks measure the vertical temperature gradient, ΔT [see white lines in Fig. 1(b) and pink and blue time series lines in Fig. 1(c)]. Five internal thermistors are positioned within the bulk fluid to measure the internal temperature fluctuations [see black lines in Fig. 1(b) and black and gray time series lines in Fig. 1(c)]. The standard deviation of each internal thermistor time series is calculated to determine the local perturbation at each location, which are then averaged to yield θ . Vertical flow velocity, u_z , is measured using an ultrasonic Doppler velocimeter. A Doppler transducer probe is positioned in contact with the interior fluid, oriented along the vertical axis of the cylinder. Natural impurities in the gallium act as particles that the ultrasonic Doppler velocimeter can acoustically sense [61]. Velocities are recorded at approximately 2 mm increments across the entire vertical length of the cell at a sampling rate of approximately 10 Hz. The characteristic u_z velocity is then calculated as a time and space rms, using the middle 50% of the cell height [see orange lines and light orange area shaded in Fig. 1(b) and the Hovmöller diagram in Fig. 1(c)].

We compare our $\Gamma \simeq 1/2$ convection cell results to those of two other aspect ratios from prior studies performed using the same experimental device. King and Aurnou

[62,63] conducted rotating convection experiments in liquid metal using a $\Gamma \simeq 1$ cell, measuring global heat transport efficiency, Nu . Vogt *et al.* [64] conducted experiments using a $\Gamma \simeq 2$ cell, measuring the Nusselt number, Nu , vertical Reynolds number, Re_z , and internal temperature fluctuations, θ . We also performed one to two direct numerical simulations (DNS) for each aspect ratio experimentally considered, as well as two cases at $\Gamma = 4$, the parameters for which are listed in Supplemental Table III [6]. We compare our findings to the asymptotically reduced planar models of Julien *et al.* [39] by incorporating their best-fit prefactor $C_J = 1/25$ in the heat transfer prediction (1). We elect to carry this prefactor through the asymptotic predictions for the Reynolds number (2) and thermal anomalies (3), as shown in Supplemental Material [6].

Figure 2 presents the measured heat transfer (Nu) and vertical velocities (Re_z) across all aspect ratios considered, plotted as a function of the buoyancy forcing (Ra). Rotating data are indicated by colored markers, while a solid black line represents the empirically found nonrotating scaling. Solid points indicate data within the oscillatory convection regime, where DNS are denoted with a black outline. Hollow points represent experiments where steady convection has additionally onset, following $Ra \geq Ra_S = (8.70 - 9.63E^{1/6})E^{-4/3}$ [65,66]. In the parameter ranges investigated here, these steady cases are not expected to follow the inertial DF scaling predicted for the oscillatory

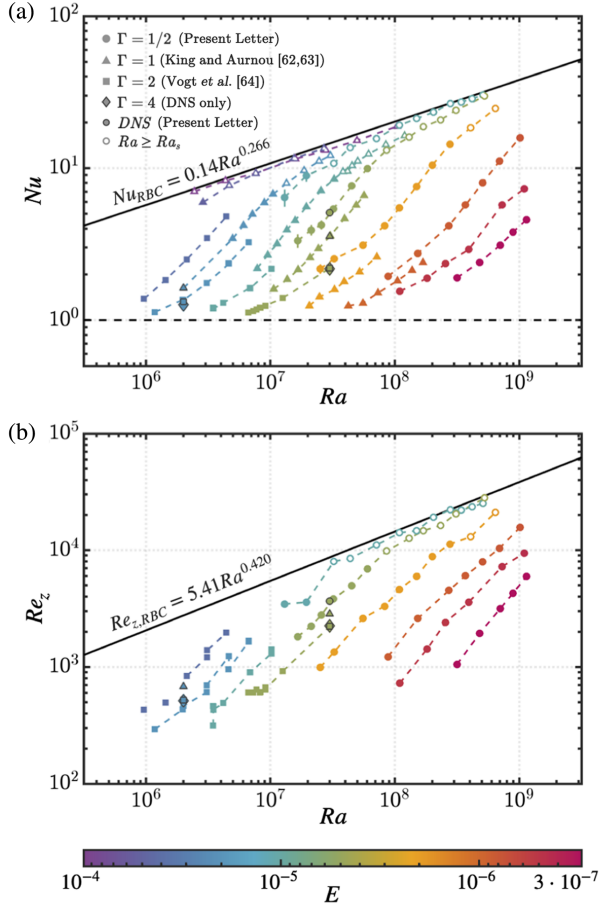


FIG. 2. Rotating convection survey measurements. (a) Global heat transport efficiency, Nu , and (b) vertical nondimensional bulk velocity, Re_z , as a function of thermal buoyancy forcing, Ra . Symbol color denotes the Ekman number, E , where red (lowest E) indicates the strongest coriolis forcing and purple (highest E) indicates weaker coriolis forcing. Symbol shape denotes the cell aspect ratio, $\Gamma = D/H$. Laboratory results from this Letter ($\Gamma \approx 1/2$) are marked as circles; those from King and Aurnou [62] ($\Gamma \approx 1$) are marked as triangles; those from Vogt *et al.* [64] ($\Gamma \approx 2$) are marked as squares; and DNS with $\Gamma = 4$ are marked as diamonds. All DNS are denoted with a black outline. Hollow points indicate cases in which the steady mode of convection has onset ($Ra \geq Ra_S$), which is used here as a transition point between inertial and steady convection regimes. The solid black line in each panel shows the nonrotating empirically determined scaling for the $\Gamma \approx 1/2$ cell from this Letter for reference.

mode (see Supplemental Fig. 1 [6]) and are therefore not included in the scaling analysis. (Under realistic geophysical conditions, Julien *et al.* [39] predict that steady rotating convective modes will also exist in the DF regime.) In addition, a weakly nonlinear regime is present near onset ($1 \leq Ra/Ra_0 \lesssim 1.5$) [67,68]. Thus, only measurements where $Ra/Ra_0 > 1.5$ are considered here. Notably, all cases exhibit high Reynolds numbers with

$3 \times 10^2 \lesssim Re \lesssim 3 \times 10^4$. Even near convective onset ($Nu \leq 2$), Reynolds numbers reach as high as $Re \approx 10^3$.

Figure 3 compares our measurements with the theoretical RDF predictions formulated with Julien *et al.* [39]’s $C_J = 1/25$ prefactor. The data is presented as colored markers, with a solid black line indicating the asymptotically reduced predictions. Power law fits to the oscillatory data (solid points) are shown as dotted lines of the same color. Inset plots display the best-fit values, and Table II (Appendix B) lists the specific best-fit power law relations for each dataset. Prefactors and exponents of unity, which are marked by a solid black horizontal line in the inset plots, correspond to the asymptotically reduced result. The oscillatory data is in good quantitative agreement with this prediction, and the DNS results are consistent with the experimental data to within the observed scatter. Notably, across all measures, the $\Gamma = 2$ and $\Gamma = 4$ DNS produce near-identical values. Hollow points (indicating $Ra > Ra_S$) clearly deviate from the diffusion-free scaling. Thus, the thermal-inertial modes follow the nondiffusive scalings, while the inclusion of low to moderate supercriticality bulk stationary modes truncates this behavior (see Supplemental Fig. 1 [6]).

The heat transfer efficiency (Nu) results in Fig. 3(a) show a close fit between the asymptotically reduced and $\Gamma \approx 2$ cell data. Decreasing the aspect ratio introduces stronger wall mode effects that enhance global heat transfer efficiency [52–55], causing the slope to deviate from the asymptotic scaling. The inset plot, which shows the best-fit values, reveals a clear trend toward the asymptotic limit as the aspect ratio increases for both the scaling exponent and the prefactor. Thus, the wider aspect ratio cell more closely replicates infinite plane layer behavior than the narrower aspect ratio cells, making it a better fit to the asymptotically reduced model result. Importantly, the $\Gamma = 2$ and $\Gamma = 4$ DNS produce the same Nu values, further verifying that at our parameters, $\Gamma = 2$ is not significantly affected by wall modes.

The thermal anomaly (θ) results shown in Fig. 3(b) exhibit excellent agreement with theory across both aspect ratios ($\Gamma \approx 1/2$, $\Gamma \approx 2$), with insets showing scaling exponents near unity. Unlike global heat transfer, internal fluctuations appear to be insensitive to wall flow behaviors such that they exclusively follow the thermal-inertial bulk scaling trends irrespective of aspect ratio value.

The vertical velocity Re_z results shown in Fig. 3(c) also strongly align with RDF theory, as they are similarly unaffected by wall modes. Overall, we find simultaneous agreement with diffusion-free predictions across all three independently measured quantities in this Letter: thermal anomalies in the bulk, velocities in the bulk, and global heat transfer. Further, we find increasing fidelity of this agreement in higher aspect ratio containers (cf. Ref. [69]), which is additionally verified by our seven DNS cases.

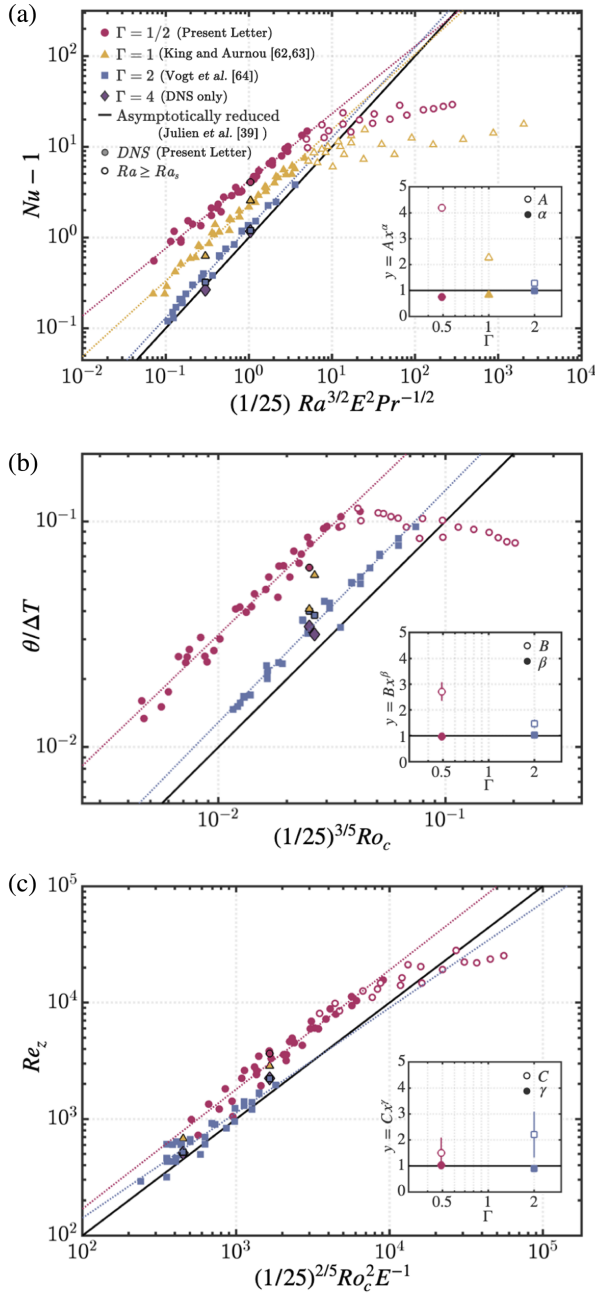


FIG. 3. Laboratory scaling results. (a) Convective heat flux relative to conductive heat flux, $Nu - 1$, (b) normalized internal temperature perturbation, $\theta/\Delta T$, and (c) measured vertical Reynolds number, Re_z , each shown as a function of the asymptotically reduced scaling result from Julien *et al.* [39]. Solid black lines indicate the asymptotically reduced predictions. Dotted lines show the best-fit power law results to each Γ dataset, where the hollow points (indicating $Ra/Ra_S \geq 1$) are excluded from the fit. Inset plots display the best-fit prefactors as hollow symbols and the best-fit scaling exponents as solid symbols, with solid horizontal lines marking the asymptotic predictions. The best-fit scaling relations are each listed in Table II in Appendix B. Across all three measured quantities, the scaling approaches the asymptotic result as the aspect ratio, Γ , increases. Other markers are the same as those in Fig. 2.

These experiments show that diffusion-free physics can exist even in relatively small, closed containers of rotating fluid. Of specific note, we find that rotating low Pr liquid metal convection in a relatively short, large aspect ratio tank ($\Gamma \simeq 2$) robustly agrees with the varied Pr results of the asymptotically reduced planar modeling study of Julien *et al.* [39]. This Letter thus verifies the C_J constant found by Julien *et al.* [39] to hold for RDF planar systems with no-slip top and bottom boundaries. In our laboratory setup, we utilize the oscillatory regime of low Pr rotating convection to achieve this goal. However, Julien *et al.* [39] find that the scaling can hold for a range of Pr assuming the criteria of rotationally constrained turbulence are met ($Ro \ll 1 \ll Re$), as expected in planetary interior flows [70,71] and in many stellar settings as well [72,73], including convection zones of massive stars where $Pr \ll 1$ and moderate Ra conditions can exist under strong rotational constraint (e.g., He II and Fe layers in [2]). Further, some numerical studies conducted with different geometries and values of Pr have also found agreement with diffusion-free scalings, albeit with differing scaling coefficients, e.g., Refs. [74–76].

Measurements of the inertial oscillation-dominated oscillatory range of liquid metal RRBC in closed cylindrical laboratory containers reveal that asymptotic RDF heat and momentum transfer can be realized on the laboratory scale. We observe these trends in measurements of internal flow velocities and thermal fluctuations regardless of tank geometry. In contrast, global heat transfer is significantly influenced by wall modes in narrow, low aspect ratio cells, with asymptotic trends predominantly found in wide, high aspect ratio cells that better resemble plane layer geometry. If wall modes can be suppressed (cf. Ref. [77]), it may be possible to achieve asymptotic heat transfer scalings in taller, more slender $\Gamma \lesssim 1$ tanks. Further, it may be possible to investigate RDF scaling behaviors using lower Pr fluids, such as liquid sodium, in which Ra_S/Ra_O attain larger values. This Letter verifies the existence of diffusivity-free convection in a standard desktop-scale RRBC experiment and demonstrates its potential as a laboratory analog for investigating the buoyancy-driven turbulence that underpins the convection zone dynamics of planets and stars.

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Data availability—The data supporting this study’s findings are available within the article. The data tables are also available in CSV format published online with the article.

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End Matter

*Appendix A: Nondimensional parameter definitions—*Parameters used to characterize the experiments are given in Table I.

*Appendix B: Summary of best-fit relations for experimental data—*Best-fit coefficients for each experimental dataset are given in Table II.

TABLE I. Nondimensional parameter definitions. Variables are ν (viscosity, m^2/s), κ (thermal diffusivity, m^2/s), α (thermal expansivity, $1/\text{K}$), g (gravitational acceleration, m/s^2), ΔT (vertical temperature drop, K), H (layer height, m), Ω (rotation rate, rad/s), q (total heat flux, W/m^2), k [thermal conductivity, $\text{W}/(\text{mK})$], u (flow velocity, m/s).

Parameter	Definition	Meaning
Rayleigh	$Ra = \alpha g \Delta T H^3 / (\nu \kappa)$	(thermal buoyancy/diffusion)
Ekman	$E = \nu / (2\Omega H^2)$	(viscous diffusion/coriolis)
Prandtl	$Pr = \nu / \kappa$	(viscous diffusion/thermal diffusion)
Nusselt	$Nu = qH / (k\Delta T)$	(total heat flux/conductive heat flux)
Reynolds	$Re = uH / \nu$	(inertial advection/viscous diffusion)
Rossby	$Ro = u / (2\Omega H) = ReE$	(inertial advection/coriolis)
Convective Rossby	$Ro_c = \sqrt{RaE^2 / Pr}$	(thermal buoyancy/coriolis)
Aspect ratio	$\Gamma = D / H$	(tank diameter/tank height)

TABLE II. Power law fits corresponding to the laboratory data shown in Fig. 3. Prefactors (A , B , C) and exponents (α , β , γ) of unity correspond to the result of the plane layer asymptotically reduced models of [39].

$Nu - 1 = A[(1/25)Ra^{3/2}E^2Pr^{-1/2}]^\alpha$		
Γ	A	α
1/2	4.20 ± 0.08	0.74 ± 0.02
1	2.26 ± 0.05	0.83 ± 0.02
2	1.29 ± 0.03	0.99 ± 0.02
$\theta / \Delta T = B[(1/25)^{3/5}Ro_c]^\beta$		
Γ	B	β
1/2	2.71 ± 0.37	0.97 ± 0.03
2	1.46 ± 0.16	1.03 ± 0.03
$Re_z = C[(1/25)^{2/5}Ro_c^2E^{-1}]^\gamma$		
Γ	C	γ
1/2	1.50 ± 0.58	1.03 ± 0.04
2	2.21 ± 0.88	0.90 ± 0.05